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RELATIVE ECONOMY OF DIFFERENT METHODS OF AIRPLANE CONSTRUCTION*

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A comparison of the relative economy of different kinds of airplane construction shows that monoplanes are cheaper than biplanes; that all-metal construction is much more expensive than mixed construction; that multi-engine airplanes are more expensive than single-engine types of the same carrying capacity and speed; that the cost of airplanes is materially reduced by increasing their size without increasing the number of engines; that the greatest economy usually coincides with the best aerodynamic and static conditions; and that the cost is always increased by safety requirements.

The lack of data on the economic aspects of different methods of airplane construction is a great difficulty. Aerodynamic and static researches, on the other hand, are supplied with accurate data by wind-tunnel and strength tests, the results of which are found in the technical press. During his many years of activity as an airplane designer many analyses of his own and of other designers' constructions have come under his notice. The first attempt to utilize these analyses was made about two and a half years ago. It proved a complete failure, owing to

the practical impossibility of drawing general conclusions from
the comparison of two different makes. The main items are labor,
general expenses, and materials. These three factors are inti-
mately related but are not of much use, because they vary so
greatly in different factories and even in the same factory with-
in a short time, according to the quantity of production. A
year later useful results were obtained by an investigation of
the manufacture of airplane wings. This method was then suc-
cessfully applied to other parts and finally enabled us to make
instructive comparisons between several quite different airplane
types.

Our task would be greatly facilitated by tables containing
the figures of the different estimates, but no German or foreign
aircraft manufacturer would release such data. It is therefore
very difficult to obtain any useful information, since the pub-
lication of estimates usually causes financial harm to the com-
pany. Moreover, the working conditions of a factory are always
affected by the quantity of production, the trend of business,
the experience of the workmen, the equipment and many other fac-
tors.

The cost of materials will be investigated first, then the
various structural components and their influence on the fin-
ished part, from which conclusions will be drawn regarding the
whole airplane. The effect of size on the methods of construc-
tion to be employed will be investigated in a similar manner.

This investigation is confined to airplanes filling the specifications of the different air ministries and therefore accepted on public service lines. If these regulations, drawn up for public safety, were disregarded, airplanes might be built cheaper, but would not sell. Unusual airplane types of more than 20 to 25 tons are beyond the scope of this investigation.

M a t e r i a l s*

Waste and purchasing expenses, for which we have empirical figures, must be added to the cost of materials used in airplane construction. Wood for spar construction must first be cut into strips and glued. The waste varies for different species of wood, being less for spruce than for pine. The fine-grained strong Polish pine, which grows on sandy ground, yields less waste than German pine. But even with Polish pine the waste is so great that pine spars and ribs became very rare in Germany after the war. During the war all spars were made of pine without requiring much additional weight. Sheet-metal and plywood plates yield waste, for which we have empirical figures. Thick sheet-metal fittings with many lightening holes yield much waste. Their thickness and the number of lightening holes can often be reduced by structural changes without affecting the weight and strength. Sheet-metal plates of the same size are used in both cases, yet in one case they are thick and considerably lightened

*Figures 1-4 were plotted eighteen months ago. Plywood prices are now much higher, while those of metal are expected to drop.

while in the other they are thin and only slightly lightened.
Thin plates are cheaper and require less work.

Economy of material means lower cost of production. The
considerable waste in the case of wood and sheet metal is obvi-
ously at the expense of the airplane manufacturer, as it in-
creases the cost of labor, the space requirements, the machine-
tool equipment and the transportation requirements. The cost of
the material, however, not only includes the waste, but also
the purchasing and delivery expenses. The purchasing cost is
much greater in aircraft construction than in other branches of
industry, owing to the very exacting material tests. Like ship-
building, aircraft construction has to rely on many subsidiary
manufacturers.

Sheet metal and fabric are subjected to tensile tests. Rods
are ball-tested and tubes and wood undergo compression tests.
Of course, rods, wood, and tubes occasionally undergo tensile
tests, but materials bought in large quantities must be checked
in a cheap and simple manner. Large deliveries of plywood are
light-tested with powerful lamps. Only samples are machine test-
ed. In the case of wood, a sample from each plank is tested by
compression. Wood, which yields little waste, can be tested at
smaller cost, since less raw material is then required for an
equal number of finished parts. The cost of nearly all materi-
als is affected by several factors.

Sheet metal and plywood can be compared only per unit of

area, the coefficients of strength and elasticity and the methods of assembly being taken into consideration. Sheet brass is the most expensive and can be obtained only in small plates. It is used in tank construction and assembled by soldering and riveting. Duralumin, which is cheaper than brass, can be obtained in very large plates or sheets of 1 mm (0.04 in.) or more in thickness. It can only be riveted, while elektron can be welded. Owing to its low specific gravity, its thickness can be easily increased, thus affording sufficient local strength for cowlings, etc. Aluminum also has good welding properties and is available in very large sheets. Sheet steel is the cheapest of all sheet metal and its price is beaten only by plywood. The cost of very thin plywood and elektron per unit weight is very high, due to the cost of production which increases with decreasing thickness of the sheets.

According to Figure 3, all thin-walled tubes of small diameter are quite expensive. Statically equivalent open sections are 20% heavier but nearly 50% cheaper. Small open sections are therefore given preference, when the cost of the special tool equipment for their assembly is warranted by the large number of pieces, especially for wing ribs. Large open sections in duralumin construction offer the double advantage of low cost and convenient riveting.

Structural Parts

a) Wing structure, fittings, spars, ribs, struts, etc.
Cantilever wings versus braced biplane wings.- From the fittings,
struts, bracings, spars, ribs, etc., the investigation of the
cost of production is extended to the whole wing. In the course
of years many forms have been evolved for the same fittings. A
certain standardization has gradually developed. The use of es-
pecially high-grade materials is of no advantage, since the ne-
cessity of maintaining low crushing and superficial pressures
seldom permit any saving in weight. In each case a certain cross
section for the absorption of the forces must be provided at the
lowest possible cost. There is more waste in making turned and
milled fittings than in composite sheet-metal fittings. Besides,
it is not always possible to make complicated fittings from a
single piece. Welding of sheet-metal parts is the only possible
means of economically producing closed hollow bodies with their
great structural advantages. As a rule, fittings properly assem-
bled from welded sheet-metal parts are the cheapest and lightest.
The use of weldable chrome-molybdenum sheet steel with its great
seam strength of 65 kg/mm² (92,450 lb./sq.ft.) is particularly
desirable in this case.

Riveted duralumin fittings are seldom lighter. Weldable
sheet steel is about as strong as refined light metals, but three
times as heavy. The edges of welded sheets are fused together
by welding wire, while the edges of riveted sheets overlap one

another. Inasmuch as the crushing pressure on the face of the
rivet holes must be kept within certain limits, the weight of
riveted joints is often increased to such an extent by the over-
lapping that the use of welded steel saves weight, especially
for closed parts.

Nearly all airplanes have more or less similar wing ribs.
In tapered wings, only two ribs are always unchanged. In Germany
wooden ribs usually consist of plywood webs with glued and nailed
flanges. Twelve to eighteen ribs are simultaneously cut from
plywood and quickly assembled, the flanges being put in jigs
and the webs glued under pressure. After 12 hours the ribs are
finished and, if necessary, lightly nailed. Several jigs are
required for letting the glue dry. Hence it is only a small
step from the number of jigs required for the cutting of plywood
webs and the gluing of ribs with uniform chord to the greater
number of jigs for tapered wings. These conditions differ from
those of duralumin ribs, which are assembled, drilled and rivet-
ed in one and the same jig. A great number of ribs can be made
in a very short time with a single machine, which, however, is
usually very expensive. Tapered metal wings are therefore less
common than wooden ones. Thin-walled welded tubular steel ribs
have been successfully used in an airplane type of which only a
few were built. Duralumin ribs are used in large English and
American flying boats and are very expensive. Even with good
machines the cost of labor for all rib types is very high. It

can be reduced only by further increasing the cost of the tool
equipment. A factory in the United States now specializes in
the production of ribs for different aircraft factories. Steel
U sections are used, the hard-soldered joints being made on
special machines. Cheap material is thus machined with a mini-
mum cost of labor. The absence of straps and rivets, with the
weakening holes, partly compensates for the greater weight of
steel as compared with light metals. This compensation can also
be achieved by greater strength of material. This method de-
serves serious consideration, despite the difficulty of protect-
ing thin-walled ribs from corrosion. Even a very little rust
greatly reduces the strength of thin walls. Thin, stamped steel
or duralumin ribs are usually heavier than tubular or U sec-
tion ribs, owing to the less favorable cross sections. Stamped
ribs, especially with short chords, can be produced in large
numbers more cheaply than U section or tubular ribs of the
same material.

The spacing of the ribs, which varies, in practice, between
20 and 40 cm (7.87 and 15.75 in.) is of considerable importance.
One strong rib is not only much cheaper, but also lighter than
two weak ribs. Narrower spacing should be used on heavily load-
ed wings for high speeds. The cost of fabric covering, sewed
to a greater number of ribs, is thereby increased. It is approx-
imately 20% of the cost of a wooden wing. The cost of the fabric
covering of a wing with many fittings, inspection flaps, and ribs,

tank openings, etc., increases approximately in proportion to the cost of the wing. It has been found more expensive to fit fabric on open metal sections than on wooden ribs, sharp edges which chafe the seams having to be avoided. This difficulty is overcome by using tubular ribs.

A distinction must be made between the spars of cantilever wings and those of externally braced wings. The flange thickness of cantilever wings must be greatly increased toward the root on account of the great bending moment. Other wings may have flanges of uniform section running to the outer joint without excessively increasing the weight. Similar considerations apply to the web, which works in shear. The cross sections in Figure 5 are now used in wood construction. Flanges have rectangular sections and are not lightened. Even for the rear spar, usually of less height, cross sections other than rectangular are avoided. It is often a mistake to try to save weight by using spars of the type of Figure 5. Two extensively used types of metal spars are shown in Figure 6.

Many kinds of struts were formerly made. Struts are compression members, for which the modulus of elasticity of the material is even more important than the compressive strength. This has gradually led to a standardization, in which high-grade chrome-nickel-steel struts are being supplanted by standard weldable-steel struts. Wooden struts seem to be definitely eliminated. Duralumin struts are used occasionally. Chrome-nickel-

steel struts are now used only in the circular form. They are usually faired to reduce drag and provided with heads cut from the solid. Tubes, heads and fairings are quite expensive. In many cases thin-walled tubes are easily dented. The difficulty of fitting the head in a water-tight manner offers the danger of internal corrosion of the thin wall. Chrome-nickel-steel struts are therefore seldom used. Carbon-steel tubes are either circular and faired or drawn streamlined without fairing. Faired circular tubes are nearly as heavy as streamlined tubes without fairing. The latter have, however, a smaller drag for practically the same strength and weight. It is also easier and cheaper to weld a water-tight head on streamlined struts than on circular ones. Streamlined struts are cheaper, owing to the absence of fairings and to the simpler head.

Struts usually have a fixed welded head with fork or eye joint on one end and a threaded socket on the other, carrying adjustable forks, eye or ball joints which are the most expensive kind. Forks with universal joints can easily be made interchangeable by means of gauges. Ball-turning lathes are provided for balls and ball seats, but they do not insure absolute roundness. It is particularly difficult and expensive to check the spherical part, especially since no standardized tools and gauges are available, as for bolts and bores.

The continuous wing of a cantilever high-wing monoplane is usually secured to the fuselage by four fittings. The spars re-

quire no connections for struts and bracings, no wing-root ribs, but only aileron hinges and bent outer edges. Wings made in several sections are more expensive. The cost is considerably increased by external bracing, which requires wing fittings and stiffening of the bottom fuselage flanges and fittings. A comparison of the different types of construction shows that struts enable but little weight reduction on commercial airplanes. They do enable, however, a valuable uniformity in the length of ribs and spar flanges, especially of fabric-covered metal wings, since uniform cantilever wings cannot be used, owing to the excessive weight of the spars.

Struts are justified on military airplanes by several considerations. Twin struts are often used to insure great structural strength, stiffness and complete absence of vibration, especially of thin wings. They guarantee full flying ability to airplanes after the failure of any one of their structural parts. Besides, more money is available for military airplanes than for commercial machines.

Cantilever biplanes with continuous lower wing require four spars instead of two, for the same total wing area, the length of these spars considerably exceeding that of the two thick spars of a monoplane. This increases the cost of labor since, regardless of the flange thickness, the spars must be machined, glued and nailed throughout their whole length, as likewise the fittings and blocks for the necessary outboard strut. Metal spars

must be drawn or rolled in exactly the same manner, but over a
greater length, and then riveted and provided with fittings.
Four bent biplane edges are more expensive than the two edges
of the corresponding monoplane. The same is true of the four
ailerons with their hinges and controls.

The weight, but not the length, of the spar flanges is re-
duced by bracing. The machined length is unchanged. The diffi-
culty and cost of producing long thin flanges outweighs the sav-
ing in material. A wing-root rib with its stiffenings costs
four to six times as much as an ordinary rib. Additional brac-
ings require more material and labor in addition to the cost of
assembling. The fittings and end ribs of divided lower wings
are more expensive than the eliminated wing portion below the
fuselage. Moreover, monoplanes have a smaller number of ribs.
The assembling of the wing is also cheaper since, aside from a
smaller number of ribs, the number of the bent edges and root
strips is also reduced. A few large ribs cost less than many
small ones. The internal bracing of monoplanes is likewise
cheaper. One-sided plywood covering as a substitute for inter-
nal bracing is usually preferable, being cheaper and producing
less drag. Present-day methods of cantilever wing construction
can be materially improved by using a single spar. Many con-
structional difficulties have been overcome by the use of wing
sections with a fixed C.G. and slightly concave lower surface.
One strong spar is considerably cheaper and lighter than two

weaker spars of the same length. The cost of connecting single-
spar wings with the fuselage might be reduced by further improv-
ing the methods of construction. The same applies to the assem-
bling of ribs and connecting members.

A cantilever monoplane is cheaper than a biplane of equal
wing area. Both the cost of the wing and the cost of the fuse-
lage are smaller. The lower wing of a biplane must also be se-
cured to the fuselage. Eight fittings are always more expensive
than four twice-as-strong fittings. Biplane struts and bracings
must also be manufactured. Braced-biplane fuselages require
special stiffenings to take the stresses of the lift wires.
Their cost is thereby increased and reaches that of the bent bot-
tom flanges of cantilever biplanes, usually required for mount-
ing the lower wing.

These considerations apply to fabric-covered light-metal
wings as well as to wooden wings. According to the type of con-
struction and tool equipment, metal edges, wing rib formers,
fittings, bracings, etc. are, on the whole, more expensive than
wooden ones. Fabric-covered metal wings produced in large num-
bers by stamping and pressing are cheaper than wooden wings.
The difference between the cost of cantilever monoplanes and
braced biplanes again becomes apparent when equal numbers are
built with the same tool equipment. Sheet-metal covering is
always more expensive and heavier than fabric covering. All-
metal biplanes are almost unknown. They would be exceptionally

expensive. The difference between the cost of fabric-covered
metal and wooden wings may be expressed as follows. Considering
the waste, duralumin in wing construction is 50 to 100% more ex-
pensive than wood with steel fittings. The cost of steel parts
is no greater than that of wood with steel fittings. Very good
tool equipments are necessary to keep the cost of labor for metal
wings at the same level as that for wooden wings. General ex-
penses are naturally increased by such installations. Any re-
duction in the cost of production necessitates an increase in
the cost of the tool equipment.

Metal is cheaper than wood, when 200 to 400 airplanes of
simple construction are built with a particularly well-designed
tool equipment. Notwithstanding the low price of the raw mate-
rial, the final cost of high-grade steel equals that of duralu-
min on account of greater machining expense. Mass production
may also greatly reduce the cost of wooden wings. In series of
twenty, the fabric covering amounts to about 30% of the cost of
wooden wings and at least as large a portion of the cost of metal
wings.

The above considerations account for the popularity of high-
wing monoplanes with tapered cantilever wings or with braced
rectangular wings for commercial purposes, especially of the
small American types. The Klemm-Daimler is a typical German air-
plane, which is now selling well. The British Simmonds "Spartan"
biplane represents a very interesting attempt to reduce the cost

(Fig. 7). This is a rival of the De Havilland "Moth." The upper and lower wings of the "Spartan" are alike. The lift wires and landing wires are of the same length and therefore interchangeable. The four ailerons are alike. The strut fittings are more expensive. The cost of this type is to be further reduced by stamping numerous identical parts. The reduction will be actually achieved, if the type sells as well as the De Havilland "Moth."

According to the above considerations, however, no price reduction can be effected comparable with that for high-wing monoplanes with continuous cantilever wings built in the same numbers. In addition to these reasons, there is another fundamental one that monoplanes have higher wing loadings and hence smaller wing areas. This is due to the ordinarily greater lift coefficient of monoplanes.

Biplanes exhibit many variations. Their historical development is a gradual transition from old and sometimes very expensive types to cheaper structural types. Three typical airplanes are compared in Figures 8-10. The stresses and lengths are given for flight case A, a weight of 1000 kg (2205 lb.) and a span of 10 m (32.8 ft.) being assumed for the calculation. A comparison can be made on this basis.

Single-field bracing is always cheaper than two-field bracing. When wing sections with fixed C.G. are used, the sum of the forces in the front and rear fields of the two-field bracing

is equivalent to that of the single-field bracing, not only in
case A, but in all cases. The stresses in the rear field of
wing sections with traveling C.P. are greater in case B. Al-
though one strong part is always cheaper than two half-as-strong
parts, the latter added together are stronger than the single
part in the case of a traveling C.P. Concentration of the sin-
gle-field bracing in a single field with two spars enables a
simplification of the fittings, provided the wings are staggered,
so that the rear spar of the upper wing is over the front spar
of the lower wing. This stagger also has aerodynamic advantages.
Forward or backward spreading of the braces for the purpose of
reducing the forces in the plane of the wing yields no appreci-
able result. Plywood covering is often substituted for internal
bracing, the former usually requiring a large cross section.
Then the case spreading produces an additional force in the low-
er fuselage longeron. The cost and weight of the wing attach-
ments are increased by the absence of right angles, the forces
in the fittings and in the lift wire being usually a little
greater.

A continuous upper wing is cheaper than a two-part wing,
the latter being in its turn cheaper than a three-part wing.
The cost is further increased by pin joints (Gerber hinges) for
three-part upper wings. The Udet Flamingo (Fig. 8) has such a
pin joint. Its stresses and bending moments are much smaller
than those of the Caspar "C 32" (Fig. 9). The wing weight of the

Flamingo is a little smaller than that of the "C 32," the ultimate load being nearly the same (wing loading minus wing weight multiplied by ultimate load factor). A further reduction in cost and in weight might have been effected by eliminating the sweepback of both wings, by increasing the dihedral angle of the lower wing and completely eliminating that of the upper wing and by making the latter continuous. Data subsequently collected by the author show that the flight characteristics are not impaired. Installing a cabane on the central section reduces the requisite number of fittings and increases the stresses and bending moments. In the case of a continuous upper wing, however, the remaining fittings then have to transmit in addition to the normal forces, only the tangential forces arising from the aileron moment about the vertical axis and are therefore very light and inexpensive. An airplane with a cabane may weigh no more than one with a central section, provided the installation of the cabane is facilitated by the fuselage, and the wing is thick enough to afford room for sufficiently strong spars. The cost may be further reduced by single-field bracing.

Experience with monoplanes shows that root bending moments are slightly reduced and drag moments greatly increased by tapering the wings. In the case of biplanes this would mean smaller stresses in the bracing and spars, with the spar sections increasing toward the wing root. At the same time the strut is shifted slightly inward; the bracing angles are better; the

length of the bent portion of the upper wing and of the bracing

wires is less; and the forces on the outboard strut are smaller

(Caspar "C 35," Fig. 10). The fuel is carried in the upper wing.

This wing has a specific weight of 7.5 kg/m² (1.53 lb./sq.ft.)

and is one of the lightest types of this size. It must, however,

be made of wood, since metal ribs and spars would be too expen-

sive. In a twin-strut single-engine biplane the stresses and

bending moments are never so much that it can be made lighter

than a single-strut biplane, unless an exceptionally thin sec-

tion is used. By doubling the number of joints and external

bracings, the advantage of small stresses is outweighed, and

the cost of the wing is considerably increased. The drag is

also increased.

b) Control surfaces.- The above considerations can be ex-

tended to the control surfaces. The horizontal empennage of

large airplanes is often as large as the wing of a small airplane,

but differs in one important point. The number of ribs which

can be made alike is very small. Fruitless attempts to use like

ribs in the horizontal and vertical tail surfaces have often

been made. Hence preference is given structural elements which

yield the greatest variety of forms with the fewest tools. Thin-

walled, weldable steel tubes are particularly suitable for this

purpose. Cheap soldered steel sections for ribs, capable of be-

ing used for wings, cannot be used for control surfaces. The

question of monoplane or biplane controls is subject to the same

considerations as that of monoplane and biplane wings. A one-piece stabilizer, like a continuous wing, is cheaper than a divided one. It is very difficult to prevent unbraced stabilizers from vibrating. The fins are usually braced. A stabilizer-adjustment device requires many good joints to prevent vibration. It is often endeavored to replace adjustable stabilizers on large airplanes by adjustable auxiliary controls or spring balancers. The cost is also reduced by the consequent lightening.

Rudders are usually made of steel tubing with fabric covering, duralumin with fabric covering, or all-duralumin. The edge greatly affects the cost and weight. Rudders with axis shifted backward have a shorter bent edge than those with auxiliary balancing surfaces. The former are lighter and cheaper on account of smaller torque and simpler form. Fabric-covered steel-tubing rudders are always cheaper than the two other types. This is due to the fact that even very small steel tubes are no more expensive than duralumin. Tubes of different sizes are on the market and can be selected according to the stress conditions. The tool equipment is also cheap. The buckling and gripping strength is greater than that of open sections, while the surface to be coated is smaller. Welded connections are light and cheap. Round tubes do not chafe seams, as open metal sections easily do. Only a few sizes of duralumin tubes of small diameter are available. Their torsional stiffness is much smaller than that of steel tubes, owing to their small modulus of elastic-

ity. The end connections are expensive and heavy. Fabric-
covered rudders made of duralumin sections and sheet are rather
heavy, usually heavier than all-duralumin rudders, since the
buckling and gripping strength of open sections is small and
their coated surface large. Riveted joints require ample flanges
with edges and more weight. All-duralumin rudders are hollow.
Their closing requires much work and considerable weight. How-
ever, being hollow, they have great torsional and bending stiff-
ness, even with thin walls, and are therefore lighter than fabric-
covered duralumin rudders. Besides, the large cross sections re-
quired by the latter have unfavorable shapes and cannot form
the covering.

c) Fuselage.- We shall consider four fuselage types, name-
ly, plywood, welded and riveted fabric-covered steel-tubing, and
all-duralumin fuselages. The four types are compared on the
basis of the cost per unit area, the airplanes being approximate-
ly of the same size. The cost increases with increasing size.

Two essentially different methods are used in plywood fuse-
lage construction. According to the one, adopted in Germany to
the exclusion of all others, a certain number of frames are first
assembled on a slip, then the longerons are fitted in and the
whole structure is covered. The other method, chiefly used in
England (De Havilland "Moth"), begins with the construction of
two sides, each framed by a top and bottom longeron. The sides
are then connected by the bottom and top and the fuselage is

completed by transverse frames, seats, etc. This method is cheaper when properly adapted to the design. The cheapest fuselage of sport airplanes is a simple type built along these lines.

Struts are now generally used in fabric-covered steel-tubing fuselages without wire bracing. This method is slightly cheaper, but its chief advantage is increased stiffness. The usually flat top is assembled in the inverted position, the lateral structures are set up and assembled by means of the bottom flange and members. After assembling internal struts and fittings, the whole structure is welded together. The quality of the welding depends on the quickness of the process. Piece work is therefore extensively employed. The welding of a seam, however, is a slow process. A saving of labor by using mechanical welding equipment requires much too expensive installations, owing to the great variety and complexity of the welded joints. According to another method the ends of the tubes are pressed into square sections and butt-riveted.* The cost of this method is greatly reduced by doing the work on mass production lines. Both types of construction are fabric-covered. Such fuselage types are now also built of drawn square section steel and duralumin tubing. The latter costs eleven to twelve times more and is 50% lighter. Butt-riveting makes no material difference.

Shell-type fuselages are built on frames. Open sections are cheaper than closed A sections and easier to assemble. They can be better protected against corrosion, which is partic-

*See Figure 19b, page 455, of the 1929 Zeitschrift für Flugtechnik und Motorluftschiffahrt.

ularly important in hulls and floats. The riveting of the cov-
ering is more than half the labor. The relation between the
prices of shell-type and steel-tubing fuselages is affected by
two factors, the first of which is production. As shown above,
the welding time cannot be reduced. Besides, the cutting of
tubes to the correct shape required for each individual connec-
tion cannot be materially expedited by mechanical means. This
differs from sheet riveting methods, the cost of which can be
reduced below that of a fabric-covered welded steel-tubing fuse-
lage by means of an adequate tool equipment, provided a suffi-
cient number of units - between 100 and 200 - is produced. The
smaller figure is for cabin and military fuselages with many
compartments. The installation of bulkheads, windows, doors,
traps, floors, wall covering, upholstery, luggage nets, plates,
instruments, etc., and the fitting of fairings, pipes, pulleys,
tanks, pilots' seats, controls, switchboards, etc., is easier
and cheaper in well-designed duralumin fuselages than in steel-
tubing fuselages with strips, brackets, etc. Hence, steel-tubing
fuselages will long be cheaper for large freight carriers with
few installations. The smooth surfaces of the square tube ends
and straps of riveted steel-tubing fuselages greatly facilitate
assembling. This fuselage type is particularly cheap when a
sufficiently large number is produced at a time. With good fit-
tings and general equipment, combined with properly equipped
workshops, this type of construction will remain superior to
all others.

Hulls and floats are made of duralumin or wood. Wood absorbs much water which separates its plywood layers, thus continually requiring minor repairs. The corrosion of light metals necessitates frequent inspection. Bent, widely spaced frames greatly increase the cost. A few strong frames are much cheaper and lighter than several light frames. They enable the use of strong coverings which can be more easily handled than very thin coverings. Little attention is given the cost of construction of seaplane bodies, due to the difficulty of combining good take-off and alighting characteristics, the former requiring small water resistance and spray production and the latter adequate resistance to strong alighting impacts. Quadrangular or pentagonal sections with straight walls and slightly curved decks give the best results. Water-tight riveted seams with short rivet spacing are quite expensive.

Experience shows that the assembly of wing and fuselage, in which the latter is designed to fit into the top or bottom of a rigid wing, is very expensive. On certain high-wing monoplanes the wing fits into the top of the fuselage. This method increases the weight and cost without affording any advantage. Braced and cantilever biplanes are likewise affected by these considerations. The cut-out fuselage portion designed for a cantilever lower biplane wing is always expensive, and offsets the cost of bracing to a certain extent. The cost of the controls depends more than the cost of any other part on their de-

sign. The control parts in the pilot's cockpit are most econom-
ically made of silumin or elektron castings in sufficiently large
numbers. The cost of the control transmission depends on the
number of changes in direction. Cables and turnbuckles are much
cheaper than rods, when straight transmissions are run from the
control stick or column, foot lever or pedal, with only one ex-
ternal pulley for each aileron. The cost of steel rods and wires
is approximately the same, when the number of pulleys with brack-
ets and stiffenings affects the strength of the transmission and
increases its friction beyond admissible limits. Duralumin rods
are always more expensive but lighter than steel rods, since all
means of reducing the cost of the former also apply to the latter.

The cost of the cabin depends on the number of seats. Mod-
ern leather chairs with elektron frames cost as much as expen-
sive easy chairs. Framed triplex windows with windlass raisers
are also expensive. As a rule there is a window for each seat.
Most of the furnishings are bought on the market and included
in the material account. The cost price of the standard-cabin
equipment now used by the Deutsche Luft Hansa, is approximately
550 marks per seat. A like amount is required for labor and
other expenses.

d) Power plant.- A steel-tubing engine bearer in front of
the fireproof bulkhead or fire wall, is lighter than a duralumin
bearer of equal strength, owing to the elaborate riveting neces-
sitated by the oblique members of duralumin joints. The cost of

a welded steel-tubing engine bearer is also greatly reduced by the low cost of the material and by the absence of complicated straps and connections.

The cost of engine installation is chiefly determined by the engine cowling which, with the fire wall, requires a large amount of sheet metal. In mixed construction, with the engine bearer and fire wall, it amounts to about 10% of the total cost of the airplane. The cost of the cowling is greatly reduced by a nose radiator since, without the latter, a cowling with good aerodynamic characteristics requires considerable stamping. As a rule, nose radiators not only reduce the weight and cost of the cowling, but simplify the water piping and reduce its cost. The weight and cost are further reduced by combining the auxiliary water tank with the upper tank of the nose radiator. Nose radiators are not the best aerodynamically, but no other arrangement offers sufficient advantages to justify its substitution for nose radiators, which are now gaining ground through evaporative cooling. The cost and weight of water-cooled engine cowlings is proportional to their area, which is slightly reduced by nose radiators.

Engine-control rods are more expensive than is usually thought. Welded steel tubular rods are cheapest, but light-metal rods are always lighter. Aluminum is good, owing to its great local and buckling strength. It is a little more expensive, but lighter. For a great buckling length it has the same modulus of

elasticity and strength as duralumin. This property is greatly
affected by structural details and space considerations. A small
space usually requires several intermediate transmission levers,
the installation of which is often difficult. A certain amount
of free space between the engine and the fire wall greatly re-
duces the length of the rods. Throttle and ignition-lever han-
dles will soon be put on the market as standardized parts. The
"Ahrends control," which replaces the bell crank, is the first
step in this direction.

The fuel piping often depends on the space between the fire
wall and the engine. A small space greatly increases the cost
of assembling. The essential parts of a large gravity tank in-
stallation include the piping from tank to strainer and from
there to the stopcock, which may also form the connection through
the fire wall and thence to the carburetor. Fuel pumps require
additional pipes to the strainer running through the fire wall
and returning through it to the stopcock. The list includes a
control manometer with piping and installation. Two pumps are
generally used for reasons of safety, and the length of the pip-
ing is increased accordingly. The fuel pump proper is an expen-
sive mechanism, the operation and general equipment of which,
including control instruments, causes further expense. Moreover,
gravity tanks are safer, this being a remarkable instance in
which safety does not increase the cost. A subdivision of the
gravity tank for reasons of safety requires two pipes, one addi-

tional three-way valve and two fuel gauges. Two tanks cost more than one and safety again increases the cost.

The shape of the tank is very important. A smaller surface area for a given capacity reduces the consumption of sheet metal and the length of soldered, welded, or riveted seams. Wing tanks usually have large surfaces and are therefore heavy and expensive. Tanks of any material mounted on rests or fittings, instead of being supported by straps or saddles, are unpopular. They are also expensive, owing to the difficulty of transmitting forces through fuel-tight connections. Figure 11 shows two examples.

Brass is now used less extensively. Its strength is about 25 kg/mm² (35,559 lb./sq.ft.). Welded seams are comparatively heavy. In relation to their bending radii, welded elektron and aluminum tanks have thicker walls and therefore require a smaller number of partitions. The shape of aluminum and elektron tanks differs from that of brass or duralumin tanks. The latter are very light, welded and fuel-tight. Very narrow welded seams are expensive when produced in small quantities. Owing to the small quantity of German production, welded elektron tanks seem most suitable at the present time, considering their cost and weight. Approximately 7% of the cost of labor for airplanes with tubular steel fuselages and wooden wings is absorbed by the fuel and oil systems.

Wood propellers with fittings cost about one-third as much

as metal propellers. Four-bladed propellers are more expensive
than two-bladed ones. Three-bladed wood propellers are cheaper
than two- or four-bladed ones, because shorter boards can be
used for their construction. The hub stresses, however, require
large cross sections and considerable weight. The machining of
the blade connections with the hub, especially for three-bladed
and one-piece four-bladed propellers is very expensive. The cost
of different propeller types of equal diameter compares as fol-
lows: two-bladed, 100%; divided four-bladed, 200%; one-piece
four-bladed, 240%; and three-bladed 220%, without hub.

c) Landing gear.- The wheels absorb half the cost of a
landing gear. V-type or bow landing gears are being gradually
replaced by those with shock-absorbing struts. Elektron and
silumin castings are now extensively used for struts with rubber
shock absorbers. Tires take 70% of the cost of a wheel and this
figure cannot be reduced by increased production. The rubber
cables of good shock-absorbing struts likewise take a great part
of their cost of construction. Inasmuch as the price of rubber
is not reduced by increased consumption, oleopneumatic struts
are coming into use. They are built on mass-production lines by
subsidiary factories and their cost will be gradually reduced to
a considerable extent. Besides, they are lighter than struts
with rubber shock absorbers. Data on their durability and tight-
ness after a long period of operation are not yet available.
Chrome-nickel-steel axles are more expensive than carbon-steel

axles, but must be frequently used for large wheels.

Effect of Size

a) Wings and control surfaces.- On extending the previous considerations regarding cantilever biplanes to a biplane with independent cantilever wings, several examples of which have already been built, the following conclusions are reached. If the joint area of the two wings is replaced by a single cantilever wing, two spars only are required which, although of larger size, are nevertheless cheaper. Besides, a smaller number of ribs and only two bent edges, two ailerons with controls, two pairs of wing-root fittings are required, instead of twice this number of parts for biplanes. Hence, a monoplane wing would be cheaper. In other words, large surfaces are cheaper per unit area than small surfaces. This is extremely important for light airplanes. For a uniform spacing of the ribs, the price of a wing per unit area is inversely proportional to its area. Biplanes of less than 50 hp are so expensive they cannot compete with monoplanes of the same power. Their upper or lower wing is very small. The wing loading, usually increasing with the size of the airplane, requires a narrower rib spacing and hence a greater number of ribs. This, however, is not very important, since the cost of the different parts, referred to the unit area, is greatly reduced with increasing size.

Enlarging fabric-covered wings reduces their price per unit

area, until a point is reached where they have to be divided.
Experience shows that the best size for dividing wings parallel
to the spars is usually reached when rail transportation becomes
impossible. Owing to the cumbersome length of the ribs, the
transportation, covering, coating and storing of the whole wing
becomes difficult. No definite figures can be given in this
connection, since they are always slightly affected by the tool
equipment and by details of construction. Under these condi-
tions very large biplanes are more economical than monoplanes.

Division of the wing parallel to the spars is very expen-
sive. Individual parts or fields of the wing are not interchange-
able, due to the extreme lightness of the front and rear portions
which lack sufficient stiffness when separated from the spar.
They always warp slightly after removal from the jig and must
therefore be firmly secured to the spar. This is very expensive
for wings divided along four lines parallel to the spars and ex-
tending over the whole span. Each box has attachment fittings
and stiffenings which provide a certain rigidity when the boxes
are dismantled. The strength of the edges to which the covering
is attached must be proportional to the tension of the fabric.
In the case of undivided wings this consideration applies to the
leading and trailing edges only, while in the present case it
extends to the division edges.

Metal-covered wings differ slightly from fabric-covered
ones. Metal covering takes a much greater part of the cost of

production than fabric covering. The cost per unit area of
spars, ribs, bent edges, ailerons and hinges, attachment fittings,
etc., decreases with increasing size, while that of the covering
remains unchanged. Inasmuch as the latter takes a great part of
the cost of the finished wing, the final cost reduction per unit
area is small. The cost of the expensive metal covering is fur-
ther increased by the numerous joints necessitated by the sepa-
ration of the wing into several boxes. Each line of separation
has two riveted seams instead of one in the undivided wing. Be-
sides, the spacing of the rivets must be reduced. The difficul-
ty of assembling leading and trailing edges 12 to 14 m (39.37
to 45.93 ft.) long, justifies the additional cost of a further
subdivision into boxes of approximately 2 m (6.56 ft.) length
to reduce the cost of assembling.

Wooden wings are seldom larger than 100 to 200 m² (1076.4
to 2153 sq.ft.). For static reasons the weight per unit area
(wing weight) increases with the size of the wing. Metal takes
a greater part of the cost of a wing than wood. Hence, the cost
per unit area of large metal wings does not increase, with in-
creasing size, in the same proportion as that of wooden wings.

The construction of airplanes exceeding 20 to 25 tons
(44,000 to 55,115 lb.) is not only a static problem involving
the weight of the airplane parts, but also one of production.
Large airplanes are heavier and more expensive, since the divi-
sion of parts increases their weight and cost. Other factors

must be added, such as stiffenings and attachment fittings of en-
gine nacelles, landing gears, wing-tip floats, handling-truck
connections, passages in the wings, etc. Seaplanes must have
water-tight compartments and doors, water-tight external rivet-
ing and inspection holes, lifting rings for transportation pur-
poses, etc. For these reasons airplanes of more than 12 tons
weight are very expensive.

b) Fuselage.- Any further increase in the size of plywood
fuselages is out of the question. This does not apply to steel-
tubing and shell-type fuselages. The surface of a fuselage un-
dergoing a conformal increase grows as the second power and its
volume as the third power of its linear dimensions. There is no
definite law for stresses and bending moments. Landing impacts
and stresses in the control surfaces are absorbed by different
parts of the airplane structure, which must be dimensioned ac-
cordingly. The relative importance of the two groups of forces
depends on the load distribution in the fuselage. The requisite
load factors decrease with increasing size of airplane. The
flange and web thickness of modern training and mail planes with
steel-tubing fuselages is about the same as for large commercial
airplanes. The change in the diameter of the tubing is nearly
proportional to the size of the fuselage. Hence, the weight of
small and large steel-tubing fuselages per unit area is usually
4.0 to 5.5 kg/m² (.82 to 1.13 lb./sq.ft.). Another very impor-
tant point is that the number of joints of the fuselage struc-

ture is practically unaffected by increasing its size. Some very large fuselages have a smaller number of joints than those of sport airplanes five to seven times lighter. Hence, the number of tubes and riveted or welded joints is practically constant for all fuselage sizes. For the same thickness of metal, the length of the welded seams or the size of the riveted sections is roughly proportional to the length of the fuselage. On the other hand, labor and material vary as the square root of the area. The cost of the fabric covering is proportional to the area. The same applies to floors, linings, etc. The percentile cost of wing, landing gear and tail-surface fittings is rather high and does not follow any definite law. Fittings cut from the solid are usually more expensive than sheet-metal fittings. The fittings for very large fuselages, the steel-tubing structure of which is cheaper on account of its size, take 50 to 55% of the cost of the covered structure, not including controls and equipment, while, in small fuselages, these figures are only 20 to 30%. The cost of the covering of very large fuselages is between 15 and 20%. The rest is taken by the steel-tubing structure and fittings (Caspar "C 35" - Fig. 10).

With increasing size the cross sections of the upper and lower flanges of shell-type fuselages are governed by the same considerations as steel-tubing fuselages. The spacing of the frames must be kept within definite limits. Certain large airplanes are provided with main frames corresponding to the string-

ers of steel-tubing fuselages. The spacing of the intermediate
auxiliary frames is independent of the size of the fuselage or
hull and determined only by the requisite stiffness of the cov-
ering. The cost of labor for the construction and erection of
these frames does not depend entirely on their size but also on
the kind of sections, corner plates, etc. The cutting, tack-
ing and riveting of the covering takes approximately 60% of the
cost and varies directly as the area. The production and attach-
ment of the fittings vary considerably, as in the case of steel-
tubing fuselages. In short, the cost per unit area of shell-
type and steel-tubing fuselages decreases with increasing size.
This cost reduction is smaller in the first case, in which the
part of the cost of the covering which is directly proportional
to the area, is greater than in the second case.

c) Landing and float gears.- The spacing of the bottom
timbers of wooden or duralumin floats depends on the estimated
water pressure. The beam spacing of walkable decks is independ-
ent of their size. Similar considerations apply to the side
walls, which take part of the water pressure. The size of a
float may be greatly increased, without changing the number of
bulkheads, hatches, and fittings. The cost can be reduced by
special attention to details. Besides, the cost per unit area
decreases with increasing size, since the closing of small hol-
low bodies is relatively more expensive than that of large ones.
The influence of the float volume is decisive. It increases as

the third power and the float area as the second power of the
increase in size. This clearly demonstrates a decrease in the
cost of production per unit volume, which is often accompanied
by a decrease in the cost of production per unit area.

The variation in the cost of the many different float gears
does not follow any definite law. For small variations, the con-
ditions are probably similar to those of steel-tubing fuselages.
In practice an increase in the total weight from three to six
tons does not, as a rule, double the weight of the float gear.
It is still more difficult to estimate the cost of the great
number of different landing gears, but something can be said re-
garding the wheels. They are loaded in proportion to their pro-
jection, i.e., the diameter by the width. The cost, varying as
this product, increases very rapidly, as much as fourfold for
an increase of the wheel load from one to two tons, or twofold
on the basis of the carrying capacity of the airplane. Above
two tons the cost increases more slowly and decreases slightly
again for very large dimensions.

d) Power plant.- Two single-engine airplanes - a large one
with an 800 hp engine and a small one with an 80 hp engine -
are compared below. They have the same power loading, their
weights being in the ratio of 1 to 10. The area per horsepower
of the engine cowling and fire wall is about the same for both.
The cost per horsepower of the engine is not much affected by
its size or type, being about the same for vertical and radial

engines. Due to the great cost of cooling installations, air-
cooled engines would have the advantage except for certain ex-
pensive parts. The bearers of vertical and radial engines are
governed by different considerations, but the size of both types
varies as that of the fuselage. The number of joints is con-
stant. The bearer of an engine is neither tenfold heavier nor
tenfold more expensive than the bearer of an engine one-tenth
as large. The small engine has a gas throttle and ignition
lever, a circuit breaker, starting magneto, revolution counter
and fire extinguisher. The large engine also requires oil ther-
mometers and pressure gauges. Water-cooled engines require wa-
ter thermometers, while fuel pumps require fuel-pressure gauges.
Hence the large engine has a very small number of instruments
per horsepower, but it also requires a starter. Both airplanes
have the same speed and are equipped with water-cooled engines,
their radiators being of the same type and having strictly iden-
tical piping. The ratio of the frontal area of the radiator to
the power is therefore constant. Its periphery and hence the
size of the water tank increases as the square root of the fron-
tal area or of the engine power. The attachment of the large
radiator does not cost ten times more than that of the small one.
The size of the water pipes is governed by considerations simi-
lar to those mentioned above for fuselage structures and engine
bearers. The analogy between two airplanes of different sizes
is of course not perfect in practice. According to the above

examples, the cost of engines per horsepower decreases with increasing size.

The size of a propeller undergoing a geometrically similar increase throughout its diameter, increases as the fifth root of the power output at a constant r.p.m. and as the fourth root of the peripheral velocity. At a constant angular velocity the centrifugal force necessitates such a strengthening of the hub section with increasing diameter, that the weight increases as the fourth power of the diameter. The cost increases as the 2.4 power of the diameter. Hence, the cost of the propeller varies either as the 2.4/5 power of the output at constant r.p.m. and peripheral velocity, and as the 2.4/4 power of the output at constant r.p.m. and peripheral velocity. This shows again a marked tendency toward a cost reduction per horsepower with increasing size.

Effect of Power-Plant Decentralization

Three or four engines are often used to increase the safety. The additional cost of decentralization on a standard commercial airplane of four to seven tons is calculated on the assumption that the single central engine has the same power as the entire decentralized power plant. In practice the latter must have a greater total power for obvious reasons.

As already shown, the difference between the cost per unit power of large and small engines is slight and follows no definite law. The same consideration applies to cowlings and fire

walls. A large engine bearer, however, is much cheaper than
three or four smaller ones. The installation of lateral engines
with cowlings and fire walls requires additional bearers, struts,
fittings, wing stiffenings and fairings. In substituting three
engines for a single central engine, the size of the cowling and
fire wall of the central engine is scarcely reduced. The number
of controls and instruments is increased three or four times.
Besides, one standard revolution counter is replaced by two and
sometimes even by four distant-reading tachometers. Difficulties
are increased by the use of long push rods and pipes. Three or
four engines require more than one fuel or oil tank and radiator.
The cost of all these parts increases with decreasing size. Sev-
eral engines together cost more than a single engine of the same
power, the cost increasing with the number of engines. The
weight is naturally increased by additional tanks and pipes.
The assumption previously made, that the engine power need not
be increased for the same pay load, is therefore incorrect, and
the power must be increased. Also the wing must be enlarged to
carry more powerful engines, this constituting another reason
for increasing the engine power. The greater drag of three or
four engines necessitates a further increase of power, if the
airplane is to maintain its speed. These considerations lead to
larger engines with greater amounts of fuel and oil, larger
tanks, etc., thus necessitating a further increase of power.
The cost increases with the number of engines.

The weight reduction attempted on large airplanes, by locating certain loads in the wings, leads to conflicting results, since the loads increase every time they are divided, and the drag is also increased. The fact that only the weight of the wing spar is reduced by a load distribution over the span is often overlooked. The other conditions remain unchanged. The wing weighs approximately 15% of the whole airplane, one-half of this figure, or 7.5%, being absorbed by the spars and struts. A reduction to 5% is the maximum obtainable by an outward shifting of the loads. This reduction is always offset by increases in the individual loads.

Conclusions

The historical development is a gradual transition to cheaper types of construction. Two-strut and three-strut biplanes are replaced by the single-strut type. The braced "Taube" was transformed into a strongly braced or cantilever monoplane. The wood-and-wire fuselage has disappeared. Sufficient experience has not yet been gained in all-duralumin aircraft construction to permit competing effectively with mixed construction as regards cost. The latter is a step toward cheaper methods of construction, as evidenced by the fact that one of the oldest German metal aircraft factories is now making fabric-covered duralumin wings.

The two calculations for the determination of the best aerodynamic and static solutions are often replaced by a single

calculation giving the most economical type of construction, especially for wings, tail surfaces and fittings, struts, bent edges, etc., for wing sections with fixed C.P. and in connection with decentralization.

The cost of airplanes, especially of single-engine types, decreases with increasing size. Their cost per unit area of wing, tail surface or fuselage is inversely proportional to the size. Engine accessories of very small airplanes are very expensive. Extra-light airplanes of very small size will eventually disappear. Such has been the fate of light motorcycles and bicycles with auxiliary motors, built six to eight years ago, and which have now completely disappeared. In an attempt to produce cheaper types, manufacturers neglected the convenience and safety of their patrons. This and the short life of their products made them gradually lose their market. Sport airplanes should therefore be kept above a certain minimum size limit, especially because any further reduction would bring no appreciable advantage. Airplanes carrying two persons must be fully reliable at cruising speed with throttled engine.

With a very few exceptions, safety increases the cost, as shown particularly by decentralization. Economic considerations lead to the conclusion that heavier engines, which are more reliable without being more expensive, are the best means of increasing safety. Large tanks and pipes are so light, as compared with their capacity, that they afford much better means of im-

proving safety than small tanks. This consideration applies to other engine accessories of high-powered single-engine airplanes.

The above considerations determine the limit of decentralization. It not only impairs the flying characteristics and reduces the carrying capacity, but greatly increases the cost of production. On the other hand, decentralization reduces the number of emergency landings only when very powerful engines are used. Otherwise, the failure of an engine reduces the safety of multi-engine airplanes instead of increasing it. These and other considerations favor powerful engines, enabling a 50% reduction of the normal power at cruising speed with a corresponding gain in safety. The advantage of several engines is problematic, since their loading increases with the number, while the degree of reliability is correspondingly reduced. Moreover, multi-engine airplanes are slower, much larger and less maneuverable in emergency landings than single-engine airplanes of the same carrying capacity.

Middle-sized ships are now built with a single engine, while only very large steamers have several engines. According to the above considerations, large engines should be built and used on middle-sized single-engine airplanes or on very large three-or-four-engine types, instead of using a larger number of lighter engines.

L e g e n d s

Fig. 12. Dornier Komet III Merkur and Fokker F VII.   The Merkur
          was formerly built in large numbers and did not cost
much more than the Fokker F VII, the fabric-covered steel-tubing
fuselage of the latter being larger and longer than that of the
Merkur.   The smaller metal-sheathed duralumin fuselage of the
Merkur costs as much as that of the Fokker, though the latter
carries two more passengers.   The wooden Fokker wing is tapered
and has differing ribs, while the strutted Merkur has like ribs
and spars and uniform continuous flanges.   A large portion of the
wing is covered with metal.   Fabric covering would probably bring
its price nearer to that of wooden wings.

Fig. 13. Short Calcutta and Dornier Superwal. Both types serve
          the same purpose.   The Calcutta is a biplane with bent
frames and duralumin ribs.   With practically the same capacity
and speed, the costs of the two flying boats, with engines, have
a ratio of 8 to 5.

Fig. 14. Albatros Schlafwagen (sleeping car) and Caspar C 35.
          Both airplanes have same power, the single-engine type
being 55 to 60 km/h (34.2 to 37.3 mi./hr.) faster with a much
heavier load.   The cost of the Schlafwagen stands in a ratio of
8 to 5 to that of the C 35, built by the writer, both airplanes
being taken without engines.   The C 35, however, was built sev-
eral years after the Schlafwagen.

Fig. 15. Rohrbach Roland and B.F.W. M 20. Both types carry eight
          to ten passengers.   The single-engine M 20 is about
15 km/h (9.32 mi./hr.) faster than the three-engine Roland.
Their costs, without engines, are 2 to 1.   The M 20 is designed
on cheaper lines.   Its wing, which is not fitted into the fuse-
lage, and its tail surfaces are partially covered with fabric.
Yet the greater cost of the Roland is chiefly due to decentral-
ization of the power plant.   The M 20 having an air-cooled en-
gine and the Roland having water-cooled engines, the decentral-
ization of the cooling system must also be considered.

<u>Fig. 16.</u> Fokker F VII and F VII 3 m.   These two airplanes, built
           on similar lines, are excellent examples of the single
and the multi-engine types.

Airplane engine	F VII 1 Jupiter		F VII 3 m 3 Titan	
Engine power	500 hp		3 × 250 hp	
Weight empty	2150 kg	(4740 lb.)	2780 kg	(6139 lb.)
Crew	160 "	(353 ")	160 "	(353 ")
Fuel	490 "	(1080 ")	560 "	(1234 ")
Pay load	800 "	(1764 ")	1000 "	(2205 ")
Total weight	3600 "	(7937 ")	4500 "	(9921 ")
Wing area	58.5 m²	(629.7 sq.ft.)	67.6 m²	(727.6 sq.ft.)
Span	19.3 m	(63.3 ft.)	21.7 m	(71.2 ft.)
Range	900 km	(559 mi.)	700 km	(435 mi.)
Maximum speed	197 km/h	(122.4 mi./hr.)	185 km/h	(115 mi./hr.)

The speed and range of the three-engine F VII 3 m are smaller than
those of the single engine F VII, since it would otherwise require
more powerful engines, more fuel and a larger wing. The costs,
without engines are 1 to 1.3, and with engines 1 to 1.35.

<u>Fig. 17.</u> Udet Condor and Focke-Wulf Möwe. The four-engine Condor
           was designed by the writer under the regulations re-
stricting airplane construction in Germany. Four 135 hp Salmson
engines had been originally planned, but were finally discarded.
With the Salmson engines the speed of the plane would have been
175 km/h (108.7 mi./hr.) instead of 162 km/h (100.7 mi./hr.) with
four 100 hp Siemens engines. The Möwe has approximately the same
speed with an ungeared 420 hp engine. A speed of 175 km/h is thus
attained with 4 × 135 = 540 hp, for the Condor, and with 1 × 420
hp for the Möwe. The speed of the Möwe with geared Jupiter en-
gine is 198 km/h (123 mi./hr.). Owing to the marked decentraliza-
tion of the Condor, the relation between the costs of the two
types is less favorable than in the case of the M 20 and the Ro-
land, the difference between the fuselage structures and all other
details being given due consideration. The Condor achieved no
great success, owing to its small engine power. The great length
of the propeller shafts did not affect their operation.

<u>Fig. 18.</u> Junkers G 24 and F 24. Several old three-engine types
           were transformed by substitution of a powerful central
engine. This arrangement is an example of retrogressive develop-
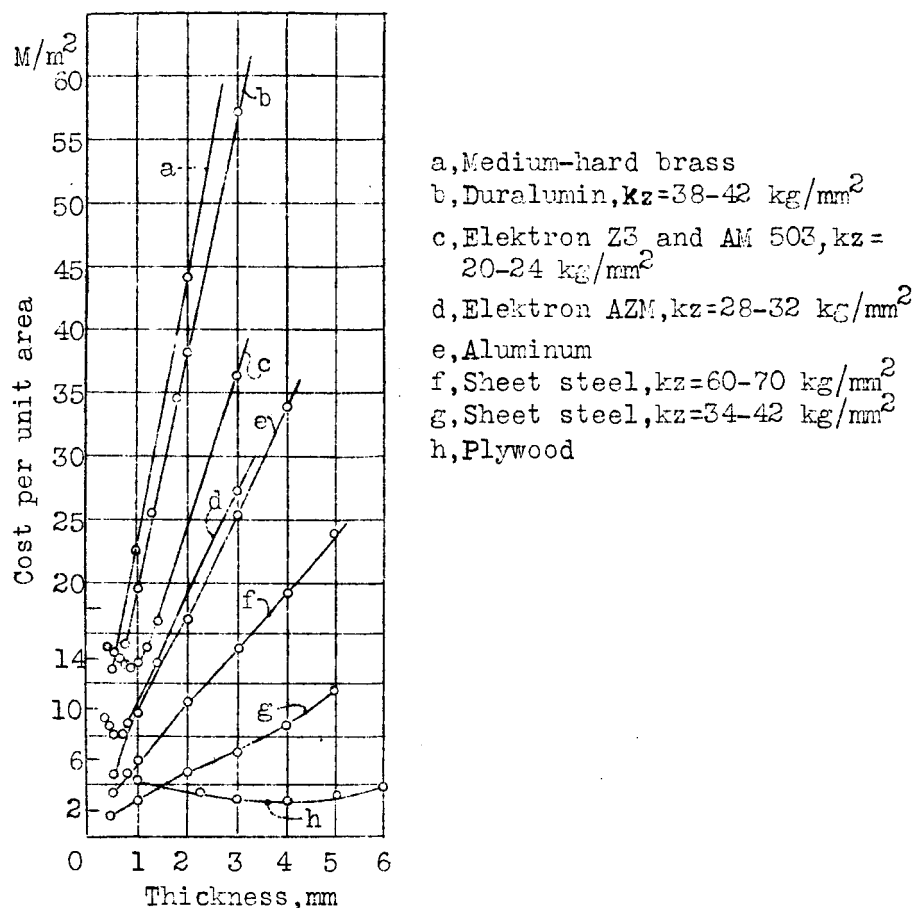ment. The F 24 was equipped with the first heavy-oil engine.

Translation by
National Advisory Committee
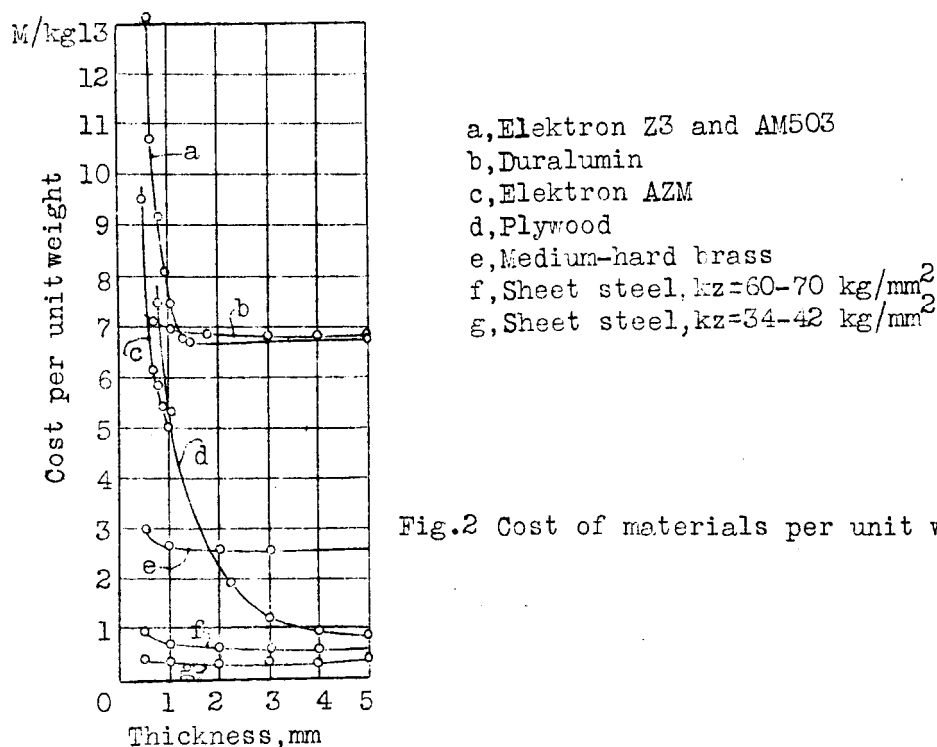for Aeronautics.

a,Medium-hard brass
b,Duralumin,kz=38-42 kg/mm^2
c,Elektron Z3 and AM 503,kz = 20-24 kg/mm^2
d,Elektron AZM,kz=28-32 kg/mm^2
e,Aluminum
f,Sheet steel,kz=60-70 kg/mm^2
g,Sheet steel,kz=34-42 kg/mm^2
h,Plywood

Fig.1 Cost of materials per unit area.

a,Elektron Z3 and AM503
b,Duralumin
c,Elektron AZM
d,Plywood
e,Medium-hard brass
f,Sheet steel,kz=60-70 kg/mm^2
g,Sheet steel,kz=34-42 kg/mm^2

Fig.2 Cost of materials per unit weight.

a=0.75 ⎫
b=1.0 ⎪ Duralumin tubes, kd=38 kg/mm^2
c=1.5 ⎬
d=2.0 ⎭

e,Equivalent open duralumin sections,
  kd=30 kg/mm^2

f=1.0,Aluminum tubes

g,Copper tubes
h=0.5 ⎫
i=1.0 ⎬ Steel tubes, kd=50 kg/mm^2
j=2.0 ⎭
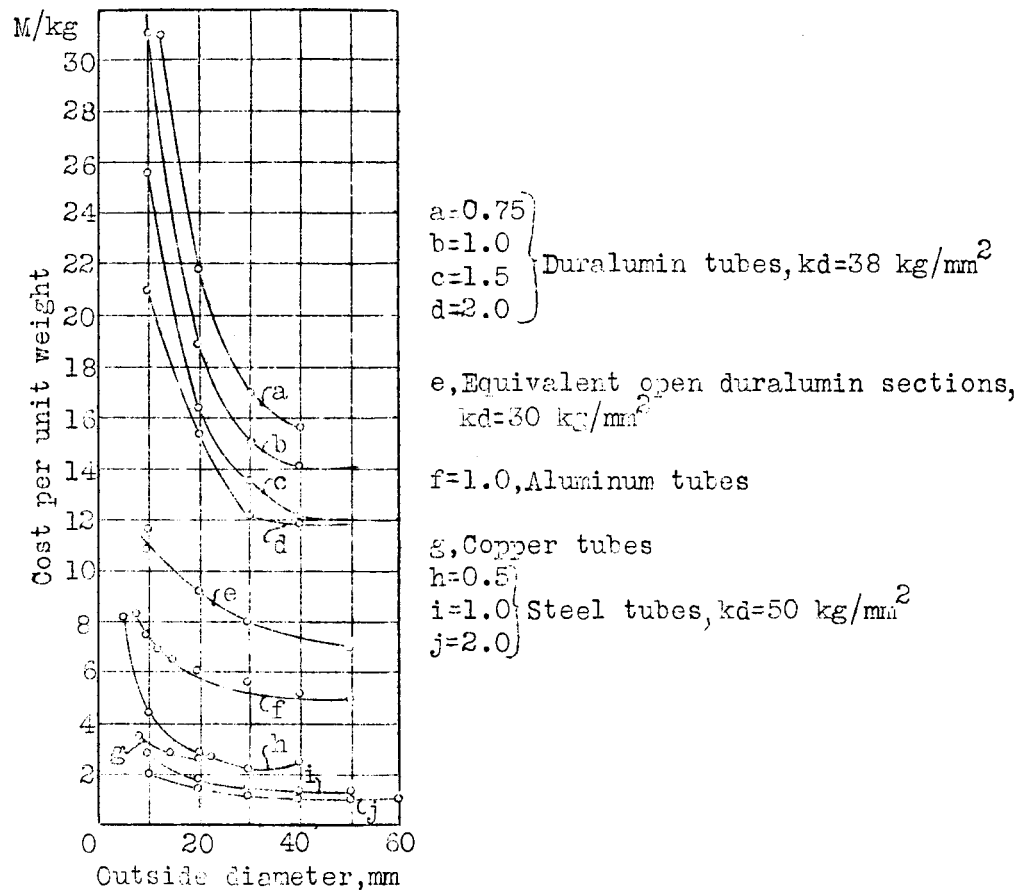
Fig.3 Cost of tubes and section metal per unit weight.

a=2.0 ⎫
b=1.5 ⎪ Duralumin tubes
c=1.0 ⎬
d=0.75 ⎭

e=3.0 ⎫
f=2.0 ⎬ Steel tubes
g=1.0 ⎪
h=0.5 ⎭

i=1.0,Aluminum tubes
j,Copper tubes
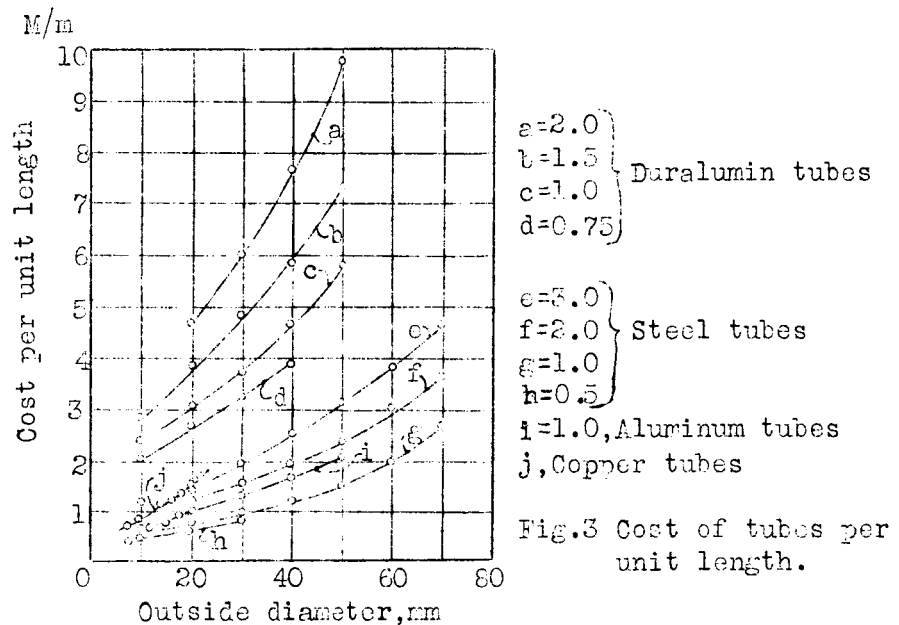
Fig.3 Cost of tubes per
     unit length.
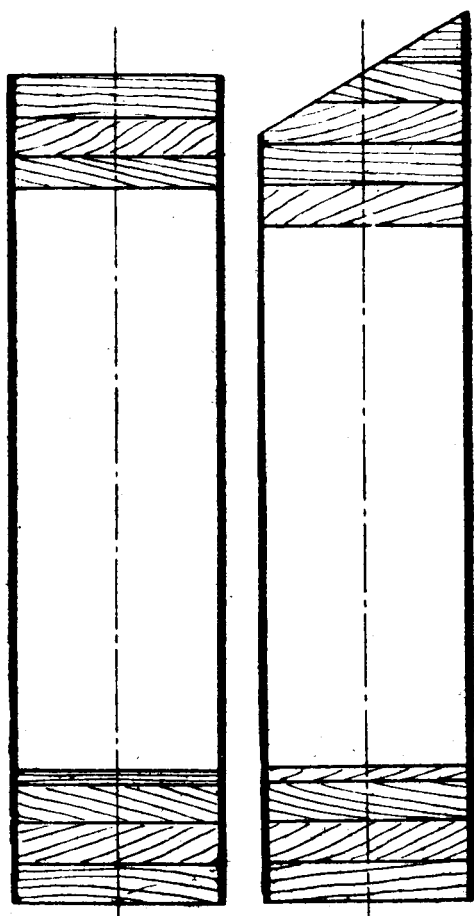
Fig.5 Sections of
typical wood spars.
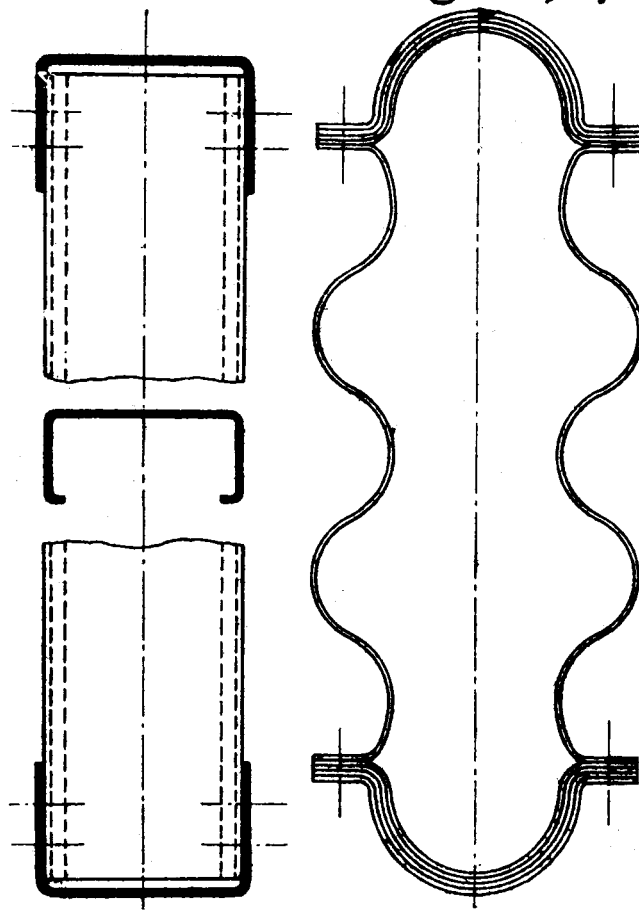
Fig.6 Sections of
typical metal spars.
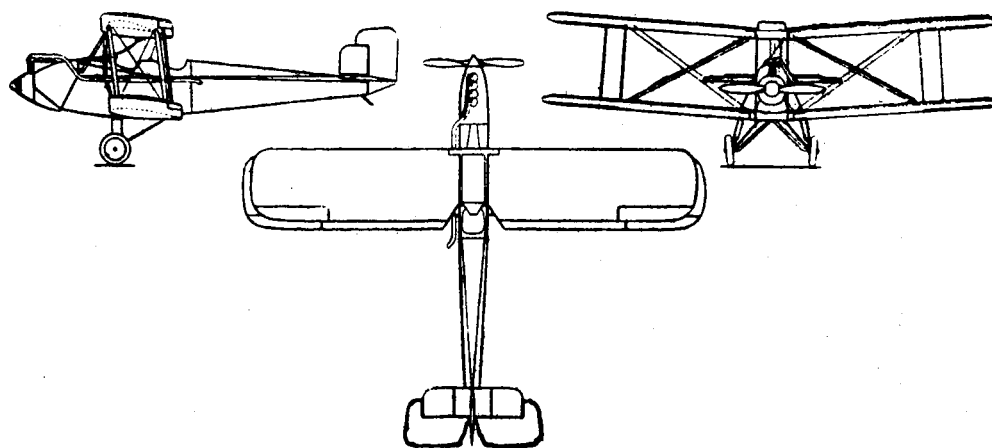
Fig.7 Simmonds "Spartan" biplane.

The assumed combined
effect of 20% is a
little high.

Height of spar is small as
compared with that of the
two following types,Figs.9 & 10

See Fig.8a for moment
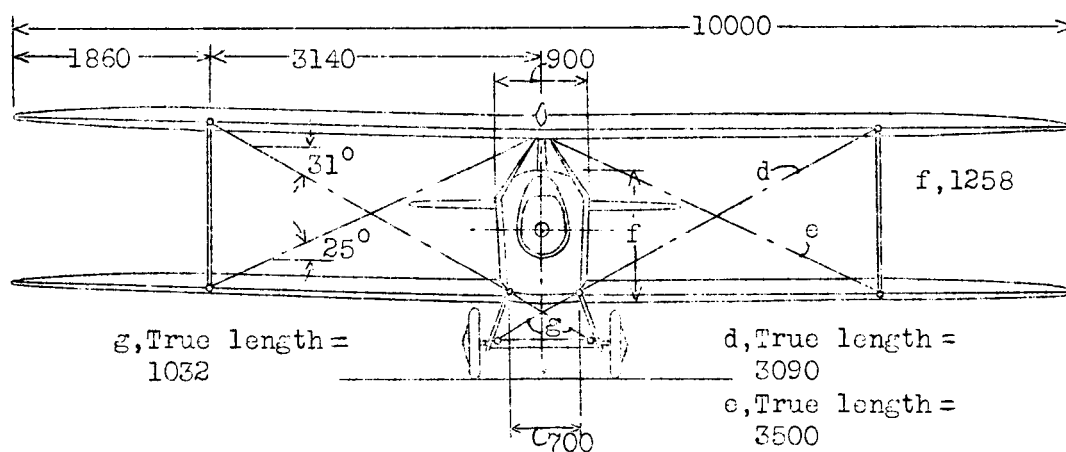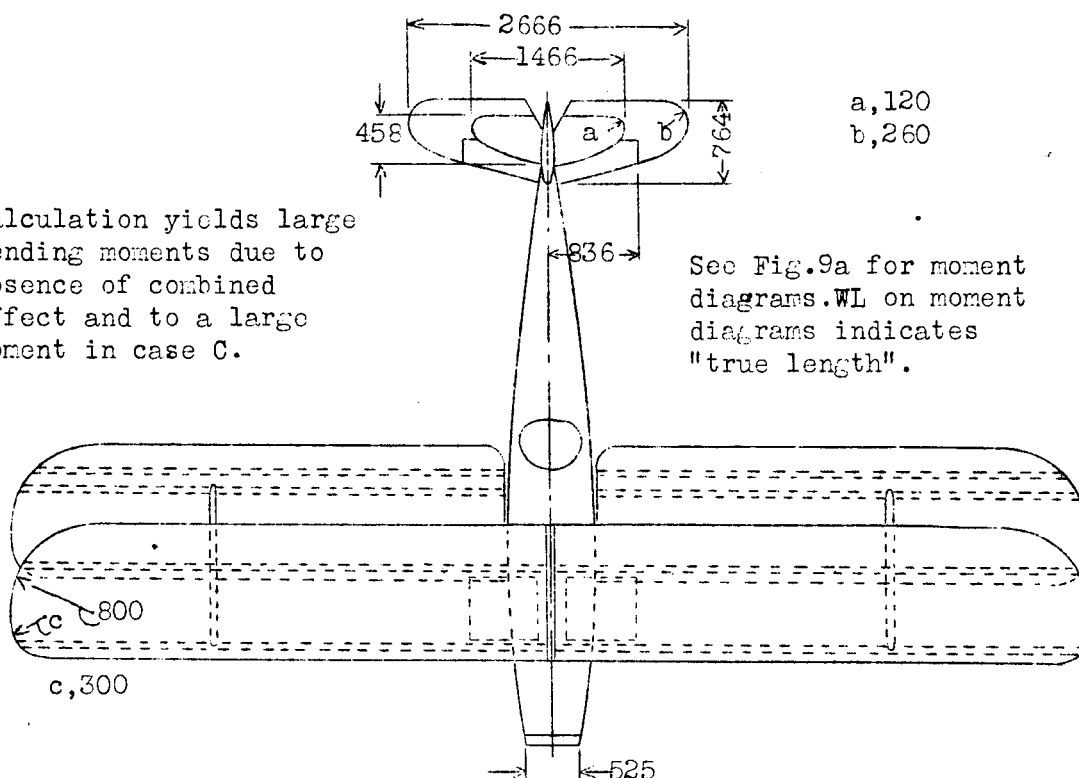diagrams. WL on moment
diagrams indicates
"true length".

3200

535   573
980   180   650

550

2200

10000
3450
900   2000

a,True length=
2875
b,True length=
3125
c,True length (rear) =
3490

i,1006

j,True length=1235
k, "   " =1360

742

7250   g,715
f,750

1520
220   d   e

h,True length=
3650

f   g

d,650
e,450

1600

1510

2800

Fig.8
Udet U-12
"Flamingo".

h

13°

Front spar

Upper wing

Rear spar

Lower wing

Front spar

Rear spar

Fig.8a Moment diagrams for U 12 "Flamingo".

Upper wing

Lower wing

Fig.11 Wing tanks in "C 36"

2666

1466

458   a   b   764

a,120
b,260
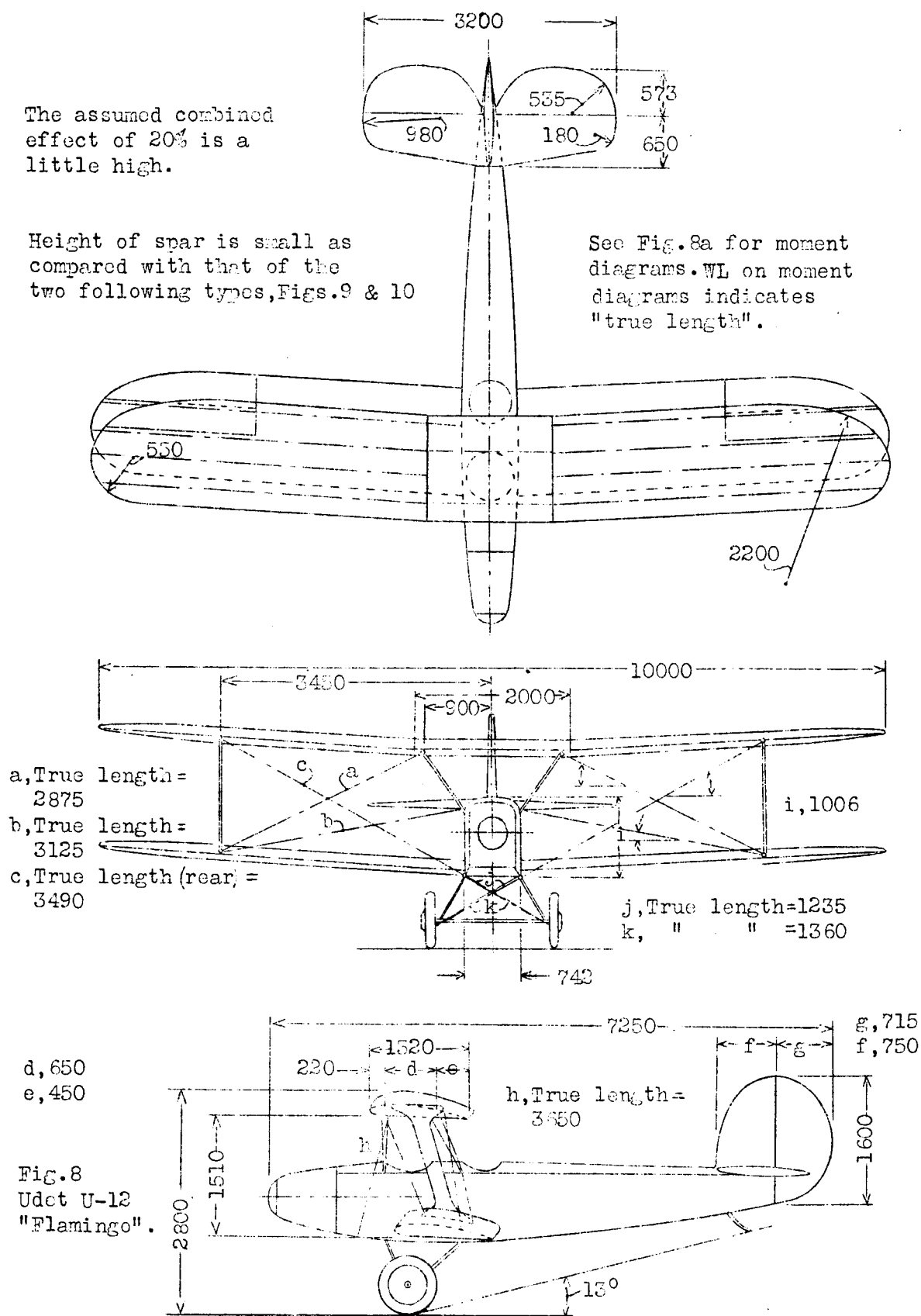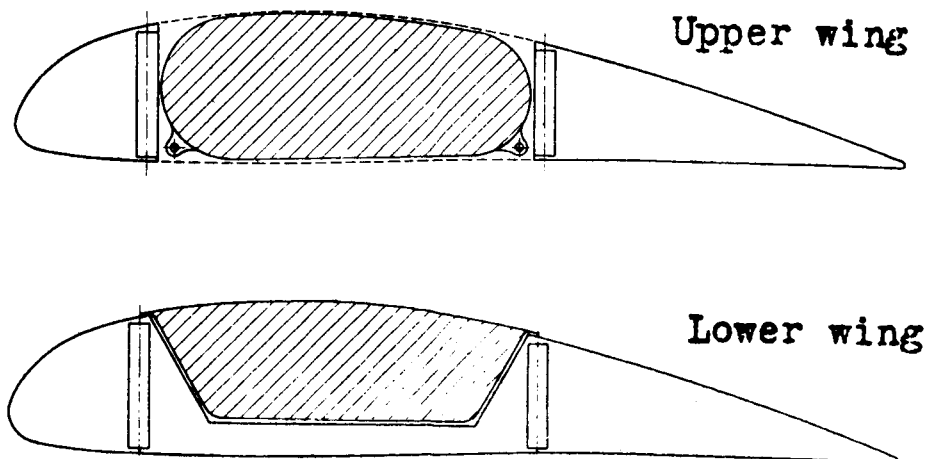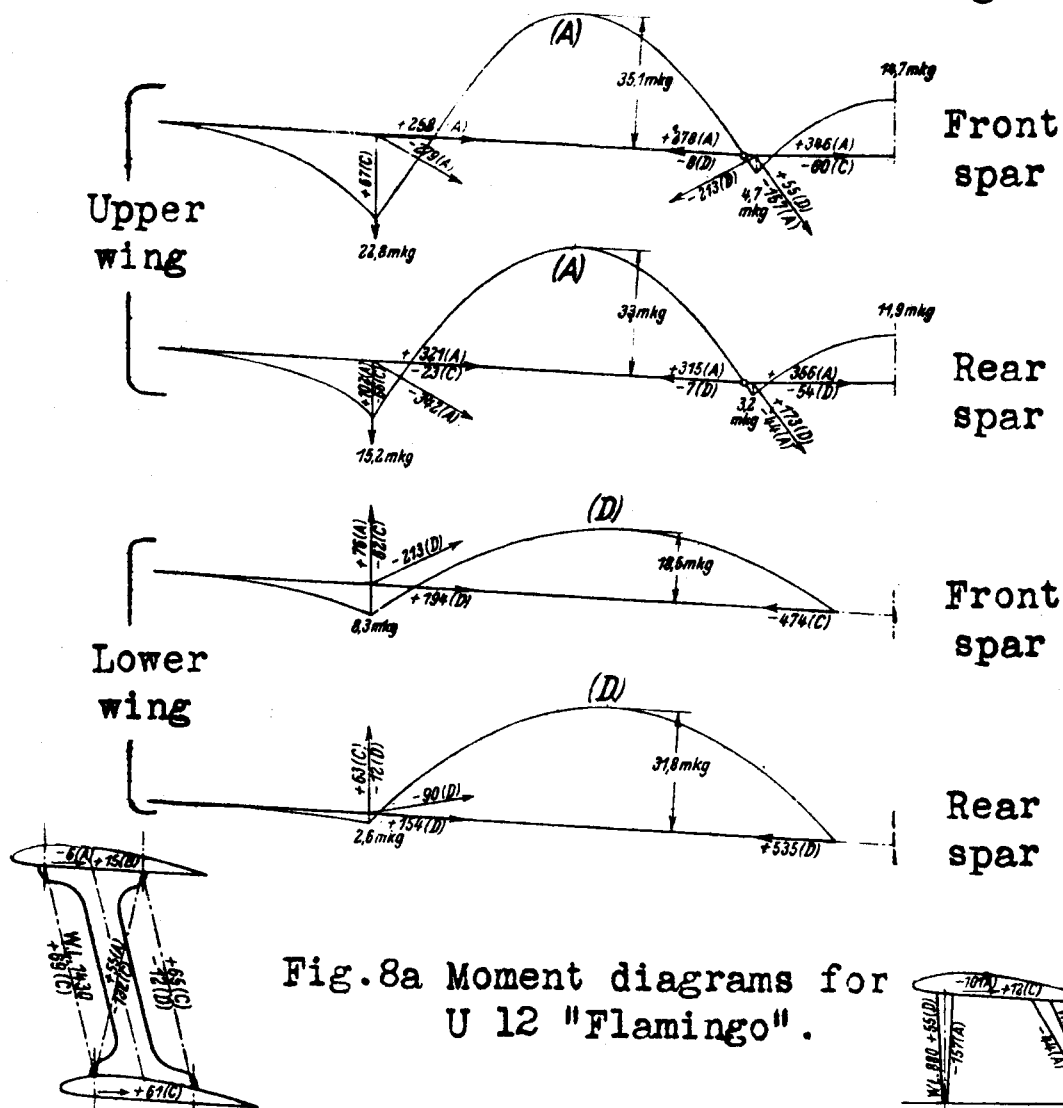
836

Calculation yields large
bending moments due to
absence of combined
effect and to a large
moment in case C.

See Fig.9a for moment
diagrams.WL on moment
diagrams indicates
"true length".

c   800

c,300

525

10000

1860   3140   1900

31°

25°

d

f,1258

f

e

g,True length =
    1032

d,True length =
    3090
e,True length =
    3500

700

* Applies to
  lower wing
  also.

5940   440

1266*
114   700   452*   200   1360

750   1560

Fig.9
Caspar
C 32.

2500

i   h

13°

h,Strut length =
    763
i,Strut length =
    550

Fig.9a Moment diagrams for "Caspar" C 32.

2900

220→ 490

420   145   305

←1250→

Spar bending moments considerably
reduced by 15% combined effect,
although the axial stresses are
but little affected by it.
A slight increase in strength
reduces weight of wing to that
of C32, i.e. from 8 to 7.5 kg/m^2.

See Fig.10a for moment
diagrams. WL on moment
diagrams indicates
"true length".

780
230

320

10000

←1600→   3400   1720

31°

26°

a   1575

1300   b

←1800→   2670

←1075→

a, True length=
   3270

c, True length=
   1935

b, True length=
   2680

* Applies to
  lower
  wing
  also.

280   ←1480→   d,630 *   f,610
       d   e   e,570 *   g,525
                            h,210

7700

←f→←g→

320

1525

g   1110
     h

2700

Fig.10
Caspar
C 35.

i   j

15°

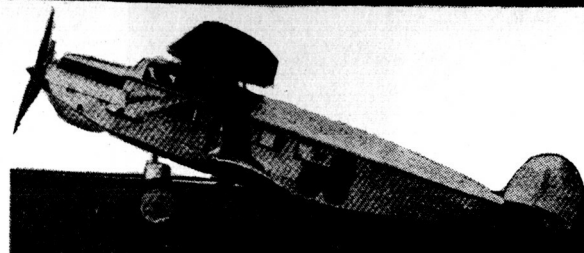i, True length=
   895

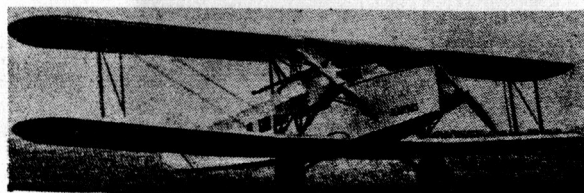j, True length=
   1315

Fig.10a Moment diagrams for "Caspar" C 35.

Fig.12
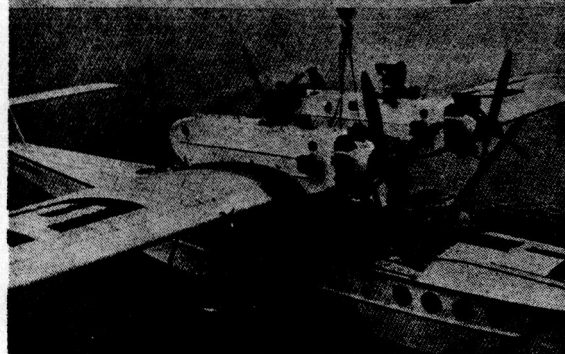
Fig.13

Fig.14

Fig.15

Fig.16

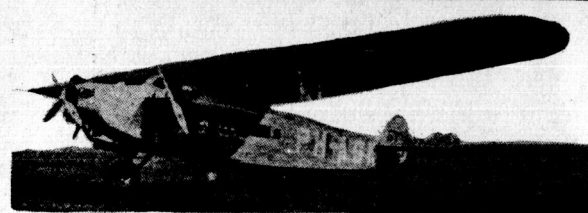Fig.17

Fig.18